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WIDE-BAND SIGNAL LEVELS IN SONAR MODELING.(U)
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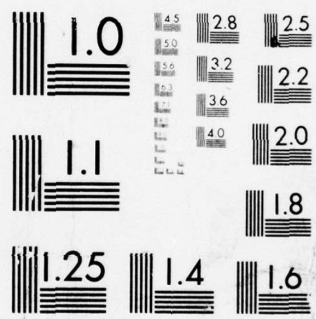

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(6) WIDE-BAND SIGNAL LEVELS IN SONAR MODELING. (U)

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(U) This technical note describes the development of a computer program for the calculation of wide-band acoustic signal levels as a part of a total computer model for sonar prediction. The analytic results of the development effort are presented here because it is believed that they will be of interest to others at Naval Undersea Research and Development Center. This note should not be construed as an official report as its only function is to present a portion of the work as information for others.

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WIDE-BAND SIGNAL LEVELS IN SONAR MODELING

I. INTRODUCTION

(U) Whenever possible, narrow-band (spectral) mathematical models are used for predicting signal levels in sonar systems; occasionally, however, models are required for systems whose bandwidth is so large that a narrow-band approximation cannot be justified. In such cases, the spectral levels must be integrated over the frequency band of interest. The integration is commonly performed using numerical techniques,[1,2] which are relatively time-consuming and inaccurate. An analytic expression, which completely eliminates the need for using the less efficient numerical techniques, has been derived and is presented in section II. It is applicable whenever the spectral intensity can be approximated as a series of straight-line segments when plotted as a function of frequency using log-log scales. This is very often the case in practice, so that the results presented here have wide applicability to practical sonar models.

II. BAND-LEVEL FOR A WIDE-BAND SIGNAL

(U) The total intensity for a wide-band signal can be obtained by integrating the spectral intensity i_s over the frequency band of interest $[f_\alpha , f_\beta]$:[3]

$$i_B = \int_{f_\alpha}^{f_\beta} i_s(f)\, df, \qquad (1)$$

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where i_B is in units-of-power/cm^2*

i_s is in units-of-power/cm^2/Hz;

and f is in Hz.

(U) When referring to intensities and intensity ratios, for convenience we shall use lower-case symbols for the actual intensity and upper-case symbols to indicate the same quantity expressed in decibels with respect to 1 μbar (dBM) or decibels (dB).

(U) Assume that i_s can be approximated over the band of interest using an expression of the general form:

$$i_s(f) = bf^m. \tag{2a}$$

Then $I_s(f)$ in dBM can be written:

$$I_s(f) = 10\ m\ \log(f) + B \qquad \text{dBM}, \tag{2b}$$

which is the equation of a straight line if log(f) is the variable. This form occurs frequently in sonar systems analysis when data points are plotted in dBM on semi-log paper.

*The reference power level is approximately 0.64×10^{-12} watts/cm^2 for water[3].

Substituting eqn. (2a) into eqn. (1) and integrating yields:

$$i_B = \frac{b}{(m+1)} (f_\beta^{m+1} - f_\alpha^{m+1}); \qquad m \neq -1, \qquad (3a)$$

or

$$i_B = b \ln \left(\frac{f_\beta}{f_\alpha}\right); \qquad m = -1. \qquad (3b)$$

(U) Equation (3) solves the problem completely, in principle. Its application to practical situations arising in sonar modeling illustrated in sections III and IV are thought to be both useful and novel.

(U) It should be pointed out that the intensity expression given in eqn. (2a) can be broken down into a product of n similar factors, each corresponding to an individual sub-system of the total sonar system, and eqn. (3) is still applicable. In this case, in eqn. (2b),

$$m = \sum_{i=1}^{n} m_i \qquad (4a)$$

and

$$B = \sum_{i=1}^{n} B_i \qquad (4b)$$

III. APPLICATION TO ORDERED-PAIR DATA

(U) Frequently, spectral intensities I_j are measured or calculated only at a discrete set of frequencies $(f_1, f_2, \ldots, f_n)$ in the frequency band of interest. Such information, when grouped in data-pairs (frequency, intensity) and arranged in increasing order of frequency, is called ordered-pair data: $(f_1, I_1), (f_2, I_2), \ldots, (f_n, I_n)$.

(U) When intensities are available only at a discrete set of frequencies, the approximate intensity at any included frequency is often obtained by linear interpolation.[*1,2] This defines a continuous functional relationship, consisting of straight-line segments between adjacent data-pairs, over the frequency band of interest, called a "piece-wise linear" function. Under these conditions, eqn. (2b) is applicable between each frequency-pair, since the data are plotted using a logarithmic frequency scale. Of course, in general there will be n-1 distinct m_j's and B_j's. Figure 1 will clarify this situation.

(U) It is clear that eqn. (3) applies individually to each linear-interpolation region, so that the total band integral for ordered-pair data can be obtained as a sum of n-1 integrals, one for each region:

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* "Linear" interpolation is actually "Logarithmic" since the independent variable is assumed to be log(f), not f itself.

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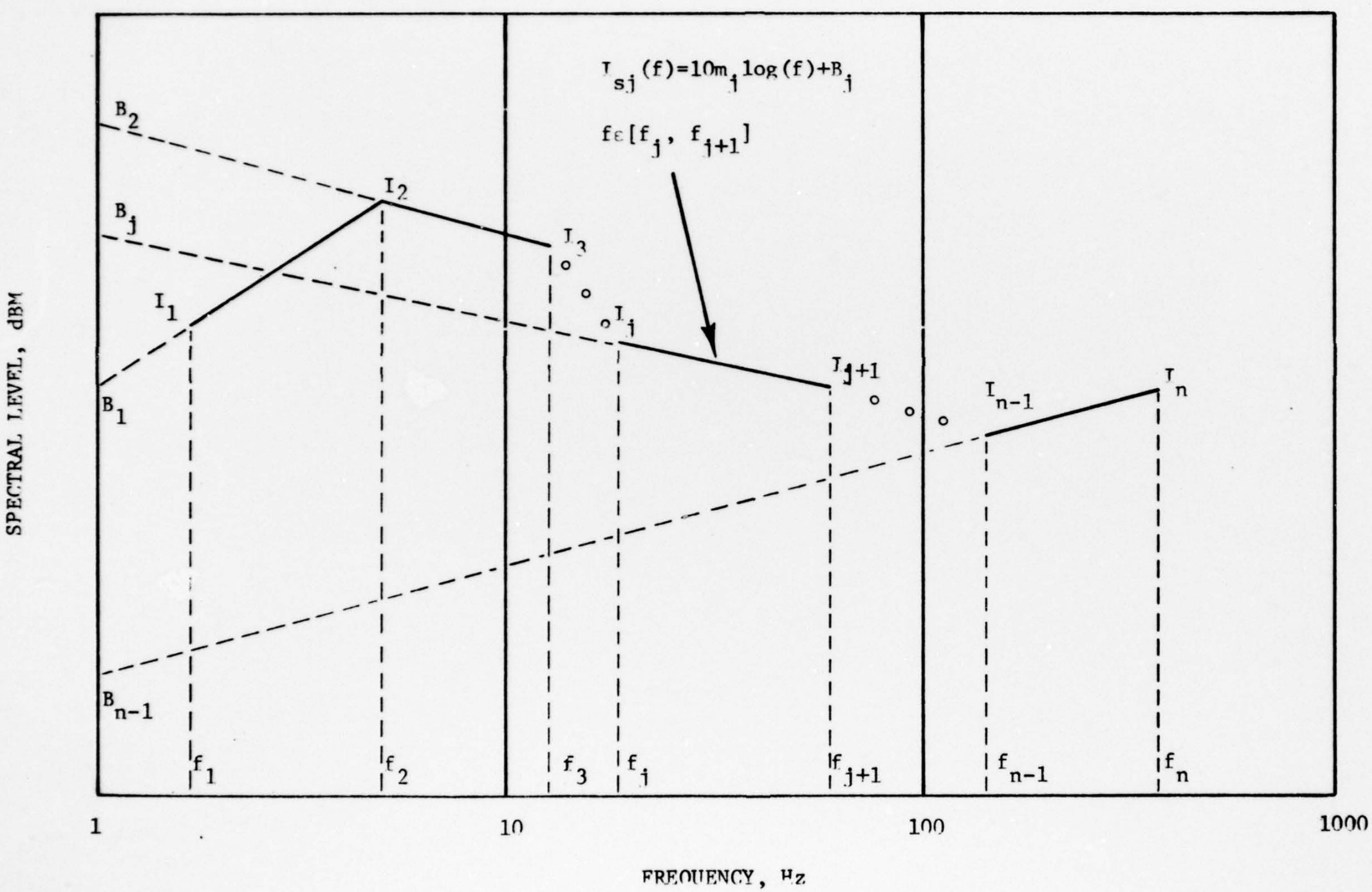

FIGURE 1

Piece-wise linear spectral signal using logarithmic frequency scale.

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$$i_B = \sum_{j=1}^{n-1} \int_{f_j}^{f_{j+1}} i_{sj}(f)df \quad , \tag{5}$$

where $$I_{sj}(f) = 10\ m_j\ \log(f) + B_j\ ;\ j = 1, \ldots, n-1.$$

Each of the n-1 integrals in eqn. (5) is evaluated individually using eqn. (3a) or (3b), as appropriate. The values of m_j and B_j are not explicitly available in the ordered-pair data given, but they can be calculated using expressions derived from the geometry of fig. 1:

$$\left.\begin{aligned} m_j &= \frac{I_{j+1}-I_j}{10\ \log\left(\frac{f_{j+1}}{f_j}\right)} \\ B_j &= I_j - \frac{\log\ (f_j)}{\log\left(\frac{f_{j+1}}{f_j}\right)} \quad (I_{j+1}-I_j) \end{aligned}\right\} \tag{6}$$

In order to clarify the method for obtaining the total band-level intensity, a step-by-step summary follows: (a) Eqn. (6) and the given data are used to obtain n-1 values each of m_j and B_j. (b) The band-level integral for each of the n-1 regions is individually evaluated, using the values of m_j and B_j for that particular region, and (3a) or (3b) as appropriate. (c) The total band-level intensity is obtained as a sum of the individual integrals for the n-1 regions, as indicated in equation (5).

(U) This proposed method is superior to the numerical-integration procedures commonly used, for at least two reasons: First, it is more nearly mathematically correct, since the integral in each region is exact, not approximate. (The only approximation is the linear-interpolation assumption, which applies to both methods.) Second, it is virtually always much more efficient, since many more regions will be required in the numerical-integration procedure.

(U) In addition to the obvious case of measured signal-level data, at least one other case of practical importance exists in which the signal levels are available as ordered-pair data: In modeling a wide-band passive sonar system, the signal level is approximated by predicting the effects of the ocean and the sonar system on the target noise spectrum. While the frequency characteristics of the sonar system are usually fairly well known, those of the propagating medium and the target noise spectrum are usually available only in a highly complicated form, or as measured data. In either case, it is reasonable to evaluate the spectral signal level only at a discrete set of frequencies in the band of interest, in which case the method presented here for obtaining total band-level is directly applicable.

IV. APPLICATION TO INCOHERENTLY-SUMMED LEVELS

(U) Frequently two or more signals, each of which can be expressed in the form of eqn. (2), are incoherently summed to obtain the spectral level of interest. In this case, the very simple method of

summing the m_i's and B_i's, given in eqn. (4), is not applicable. A general expression applicable to this situation is derived in section IV.B; a special case of practical importance will first be treated in section IV.A.

A. Empirical Expressions for Sea and Ship Noise

(C) Three empirical expressions for predicting ambient sea and ship noise are available.[4,5] The equations, which are based on the Knudsen curves and CDR Fridge's data are:

$$N_o = -42 - 16.67 \log (F) + 10.35 \log (h) \qquad \text{dBM/Hz} \qquad (7)$$

$$N_w = -42.9 - 16.67 \log (F) + 2h \qquad \text{dBM/Hz} \qquad (8)$$

$$N_v = -44 - 16.67 \log (F) + 1.5v \qquad \text{dBM/Hz} \qquad (9)$$

where N_o, N_w, and N_v are, respectively, the ambient ocean noise, the wave component of ship noise, and the velocity component of ship noise;

F is the frequency in kHz;

h is the wave-height in ft;

v is the ship speed in kts.

(U) In sonar predictions, the noise sources whose levels are predicted by equations (7), (8), and (9) are assumed to add incoherently. Thus, eqn. (7) alone predicts the ambient ocean noise in the absence of the ship, the incoherent sum of equations (8) and (9) predicts the total additional noise N_D due to the presence of the ship, and the incoherent sum of all three equations predicts the total ambient ocean noise level with the ship present N_T.

In equation form,

$$N_D = 10\ \log(n_w + n_v) \qquad \text{dBM/Hz} \qquad (10)$$

and

$$N_T = 10\ \log(n_o + n_w + n_v) \qquad \text{dBM/Hz} \qquad (11)$$

(C) The expression for the total spectral noise level obtained by combining equations (7), (8), and (9), using (11), is useful in itself; it will be obtained prior to applying eqn. (3) for the total band level. Summing the intensities incoherently, we have:

$$n_T = (10^{-4.2} \cdot h^{1.035} + 10^{-4.29} \cdot 10^{0.2h} + 10^{-4.4} \cdot 10^{0.15v})\ F^{-1.667} \qquad (12a)$$

or

$$N_T = -40 + 10\ \log\left[\frac{h^{1.035}}{1.5849} + \frac{10^{0.2h}}{1.9498} + \frac{10^{0.15v}}{2.5119}\right] -16.67\ \log(F)\ \text{dBM/Hz} \qquad (12b)$$

(C) Since eqn. (12b) is in the proper form, eqn. (3a) can be directly applied to obtain the ambient noise band level in the water, for any frequency band $[F_1\ ,\ F_2]$ over which equations (7), (8), and (9) are applicable:

$$N_B = -10 + 10\ \log\left[\frac{h^{1.035}}{1.5849} + \frac{10^{0.2h}}{1.9498} + \frac{10^{0.15v}}{2.5119}\right] + 10\left[\log \frac{F_1^{-0.667} - F_2^{-0.667}}{0.667}\right] \quad \text{dBM} \qquad (13)$$

where 30 dB has been added to allow for integration with respect to frequency in kHz. The argument of the logarithm in the third term of eqn. (13) will be positive for the condition $F_2 > F_1$, as was assumed. The denominator in this term can be combined with the other constants; it has a value of approximately 1.75874 dB.

(U) Equation (13) gives the noise band level in the water. A more useful level is at the output of a sonar system. Equations for the system functions, if available in the proper form, can be combined with eqn. (12b) using eqn. (4). This has been done for the SQQ-23 PAIR system, and the results will be given here as an example.

(C) The PAIR system functions required to obtain the output noise level are the system directivity index D_I and amplifier gain G. The expressions are:[2]

$$D_I = 11 + 20 \log(F) \qquad \text{dB} \qquad (14a)$$

$$G = 16.6 \log(F) \qquad \text{dB} \qquad (14b)$$

(C) Equation (12b) and (14) can be combined using eqn. (4). It should be noted that quieting terms, amounting to 1 dB and 3 dB, have been applied to equations (7) and (9), respectively, so that the constants differ slightly from those previously given. The spectral level (integrand) obtained is:

$$n_{sp}(F) = 10^{-1.1} \cdot (10^{-4.3}h^{1.035} + 10^{-4.29}.10^{0.2h}$$

$$+ 10^{-4.7}.10^{0.15v})\ F^{-2} \qquad (15a)$$

or

$$N_{sp}(F) = -51 + 10 \log\left[\frac{h^{1.035}}{1.9953} + \frac{10^{0.2h}}{1.9498} + \frac{10^{0.15v}}{5.0119}\right]$$

$$- 20 \log(F) \text{ dBM/Hz} \qquad (15b)$$

The expression for the corresponding band level, over a frequency band $[F_1, F_2]$ is:

$$N_{bp} = -21 + 10 \log\left[\frac{h^{1.035}}{1.9953} + \frac{10^{0.2h}}{1.9498} + \frac{10^{0.15v}}{5.0119}\right]$$

$$+ 10 \log\left[\frac{1}{F_1} - \frac{1}{F_2}\right] \quad \text{dBM} \qquad (16)$$

where 30 dB has again been added to allow integration with respect to frequency in kHz. In the PAIR system, F_1 and F_2 are known constants, so that the last term in eqn. (16) can be evaluated and written into the equation. Actually, there are three different passive bands used in the PAIR system: 1.0 to 1.8 kHz; 1.0 to 2.5 kHz; and 1.0 to 6.0 kHz. The corresponding constants for the third term in eqn. (16) are: -3.5218, -2.2185, and -0.7918.

B. General Expressions for Incoherently-Summed Sources

(U) In the general case, there will be n signal sources whose intensities are assumed to add incoherently. Suppose that the intensity of each source is given by an expression of the form of eqn. (2b):

$$S_k = 10m_k \log(f) + B_k;\ k = 1,\ldots,n.$$

The corresponding net spectral level, assuming incoherent-source summing, is:

$$s_s(f) = \sum_{k=1}^{n} b_k\,(f)^{m_k} \tag{17}$$

(U) Equation (17) can be integrated using eqn. (3a) or (3b) on each term as appropriate. The resulting intensity over a frequency-band $[f_1\ ,\ f_2]$ is:

$$S_B = 10 \log \left[\sum_{k=1}^{n} \left\{ \begin{array}{ll} \dfrac{b_k}{m_k+1} \left(f_2^{\,m_k+1} - f_1^{\,m_k+1} \right) & m_k \neq -1 \\ \text{or} \quad b_k \ln\left(\dfrac{f_2}{f_1}\right) & m_k = -1 \end{array} \right\} \right] \tag{18}$$

V. CONCLUSIONS

(U) Well-known integral relationships have been applied to practical sonar intensity functions to obtain equation (3), a general expression for total wide-band intensity. The basic assumption is that the spectral levels of interest can be expressed as in eqn. (2b), which is frequently the case in practice.

(U) Equation (3) was applied to the important special cases of measured data and incoherently-summed sources, with the results given in sections III and IV. As an example of the latter case, expressions were derived using empirical expressions for Knudsen's curves and CDR Fridge's data for ambient sea and ship noise. Results for the passive SQQ-23 PAIR system were also presented.

(U) Computation time using the expressions derived will normally be very much less than that of previously-used numerical methods, yet the results obtained will be more accurate.

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